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Superconductor Requirements for the HFM Program at Fermilab

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Abstract – Nb_3Sn strand parameters required for the high field accelerator magnets being developed at Fermilab for a post-LHC Very Large Hadron Collider are discussed.

I. INTRODUCTION

Fermilab, in collaboration with other U.S. National Laboratories, is working on the development of high field superconducting magnets for a Very Large Hadron Collider. Two magnet designs (shell or cos-theta type and block/common coil type) are being studied [1,2]. Preliminary magnet design parameters include:

- nominal operation field of 10-12 T,
- operation field range B_{nom}/B_{inj} of 15-20,
- good (acceptable from the beam dynamics viewpoint) field quality over 2/3 of the magnet bore in the operation field range,
- magnet bore of 30-45 mm,
- full-scale magnet length of 10-15 m.

A low magnet cost is also one of the most important parameters for these magnets.

To provide nominal operation fields above 10 T, NbTi strands cannot be used even at 1.9 K, and a new type of superconducting strands have to be considered. Recent progress in Nb_3Sn strand development and commercial availability of this superconductor make it very attractive for the use in high field accelerator magnets.

The superconducting Nb_3Sn phase is formed during a high temperature heat treatment. A relevant characteristic of this material is its brittleness, which requires specific approaches to magnet fabrication. Two technological approaches are adopted for magnet fabrication using Nb_3Sn strands: wind & react and react & wind. Both these approaches are under study at Fermilab.

This note presents a description and the main parameters of conceptual designs of the high field Nb_3Sn superconducting magnets developed at Fermilab. The requirements to the Nb_3Sn strand used in these magnets are discussed.

II. MAGNET DESIGN AND TECHNOLOGY

A. Magnet Designs

The details of the high field magnet designs developed at Fermilab for a VLHC are reported in [1,2]. The magnet cross sections are shown in Figures 1 and 2. The design parameters are summarized in Table I.

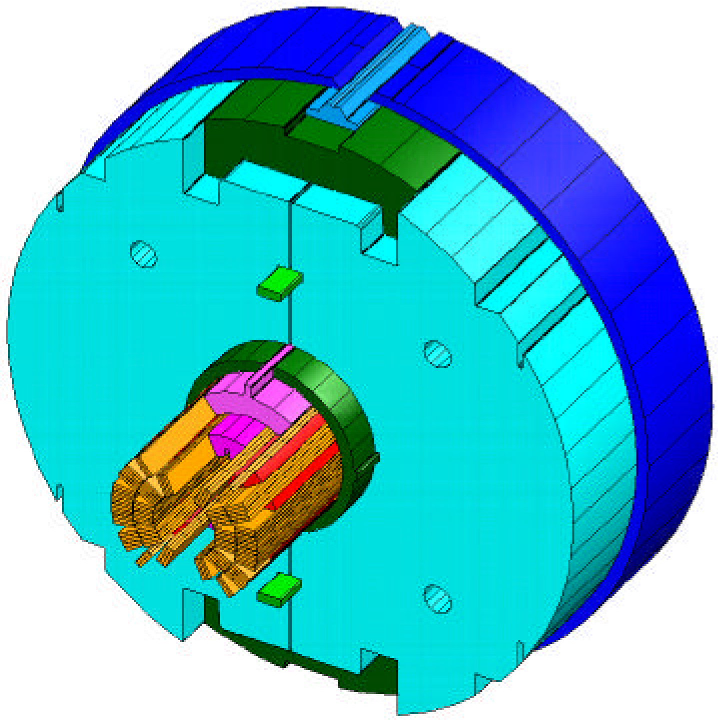

Figure 1. Cos-theta dipole magnet (single bore configuration is shown).

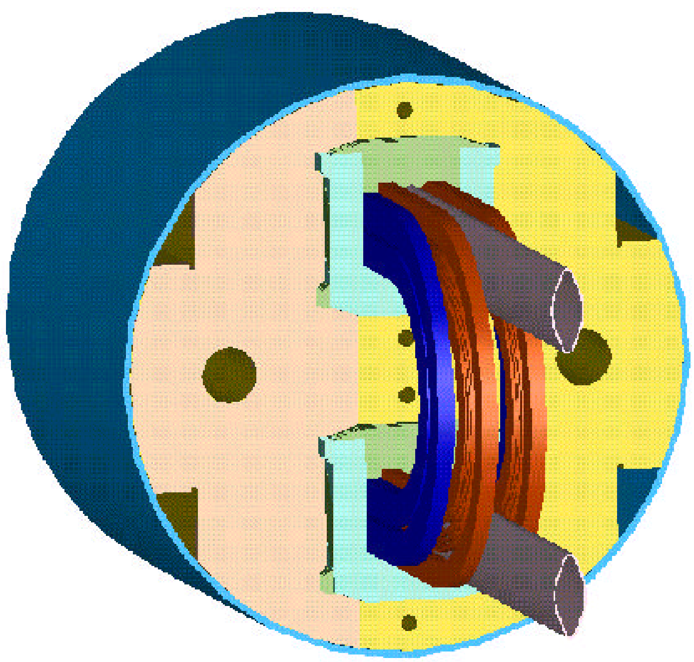

Figure 2. Common coil dipole magnet (this design is applicable only in two bore configuration).

Table I. Magnet design parameters.

Magnet design	Cos-theta	Common coil
Magnet bore, mm	43.5	30
Number of layers	2	2
Transfer function, T/kA	0.555	0.74
Current @ 11 T bore field, kA	19.82	14.86
Stored energy @ 11 T*, kJ/m	241	420/2
Magnet inductance*, mH/m	1.50	4.29/2
Total coil area*, mm^2	2233	2588

* - per one aperture.

Both magnet designs utilize Nb_3Sn Rutherford-type cables. The cable parameters are summarized in Table II. The cos-theta magnet design is based on the wind&react technique. A high temperature heat treatment will follow the half-coil winding and coil assembling stage. For the common coil magnet design a react&wind approach is possible and highly preferred. The cable will be reacted on the large diameter spool, insulated and then wound into a racetrack coil.

Table II. Nb_3Sn cable parameters.

Magnet design	Cos-theta	Common coil
Number of strands	28	41
Strand diameter, mm	1.00	0.7
Cable width, mm	14.24	15.04
Mean thickness, mm	1.800	1.24
Keystone angle, degree	0.9	0.0
Packing factor	0.884	0.866

B. Magnet technology

Two technological approaches are studied to fabricate Fermilab’s magnets out of brittle superconductors: wind&react for the cos-theta magnet design and react&wind for the common coil magnet design.

The technological steps for the wind & react approach include:

- cable fabrication from non-reacted strands,
- cable insulation with a high temperature insulating material (ceramic or S2-glass tape/sleeve),
- half-coil winding, impregnation with a ceramic binder and low temperature curing for coil pre-forming and sizing,
- two half-coil assembly in a reaction mold and high temperature heat treatment to form the Nb_3Sn superconducting phase,
- coil impregnation with epoxy and curing,
- coil assembly with iron yoke and prestressing.

The technological steps for the react & wind approach include:

- cable fabrication from non-reacted strands,
- cable high temperature heat treatment to create the Nb_3Sn phase,

- cable insulation with Kapton or fiber-glass tape,
- coil winding and low temperature curing for coil sizing,
- coil impregnation with epoxy and curing,
- coil assembly with iron yoke and prestressing.

Some of the above technological operations can deteriorate the superconductor performance and thus reduce the magnet operation parameters. To compensate for this effect the superconductor degradation during magnet assembly and operation should be taken into account in strand specifications.

III. CONDUCTOR REQUIREMENTS

A. Critical Current Density

The dependence of the required strand critical current density at 12 T and 4.2 K on bore field is plotted in Figure 3 for the cos-theta and common coil magnet designs. The coil Cu to non-Cu ratio is 0.85:1 for both designs. To determine the required critical current density of the virgin strands for full-scale magnets from this plot, one should take into account several factors such as magnet critical current margin, critical current degradation and Cu to non-Cu ratio.

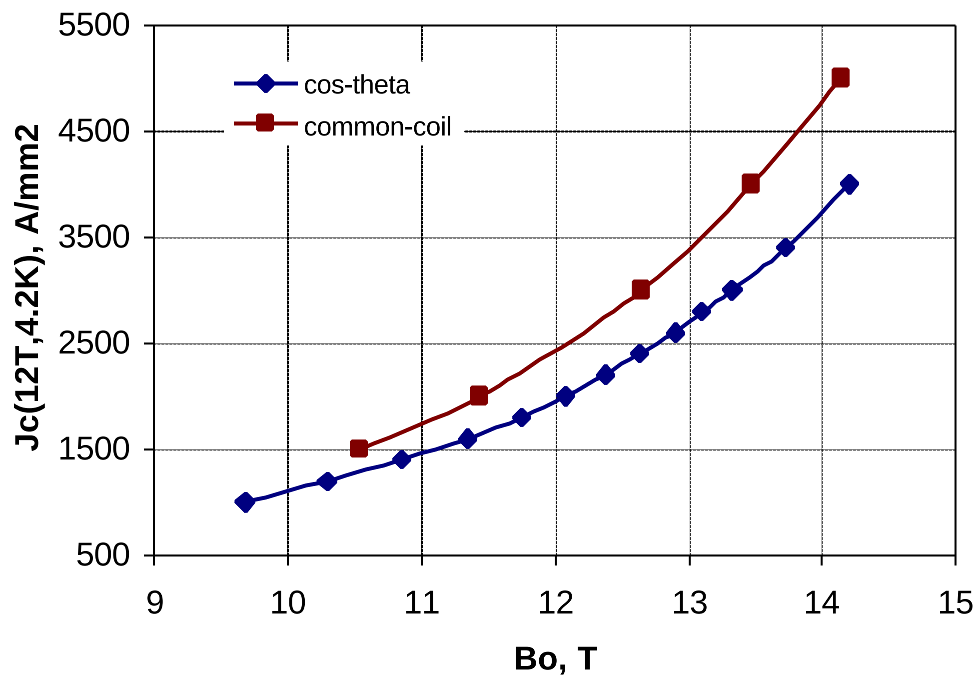

Figure 3. Required strand critical current density @ 12 T, 4.2 K vs. maximum field in the magnet bore.

<u>Critical current margin.</u> The critical current margin is defined as a difference between the magnet critical current and the nominal operation current. It is essential to reduce the effect of magnet training, re-training and quench current degradation on the accelerator performance. Those values are not established yet for Nb_3Sn accelerator magnets. For the 11 T MSUT (Twente University) magnet training range was quite small,

less than 5% of the expected critical current [3]. For the 13 T D20 (LBNL) the training range was about 20% [4]. The critical current margin required for Nb_3Sn accelerator magnets should be further studied experimentally in a framework of a magnet model R&D program. For this study a 15% margin was chosen, based on the large experience with NbTi accelerator magnets and on the above training data for the Nb_3Sn short models.

Critical current degradation. Several factors during cable and magnet fabrication and during magnet operation cause the reduction of critical current density in Nb_3Sn strands with respect to virgin strands. They are:

- Strand mechanical deformation during cabling;
- Cable bending during coil winding (only for reacted cables);
- Cable transverse compression during coil pre-stressing, and stress due to Lorentz forces during operation.

The critical current degradation depends on strand and cable designs, cable and magnet fabrication technology, magnet operation parameters. All these effects have yet to be studied. A total 10% of I_c degradation in the cable was adopted here for the cos-theta magnet [5], and of 20% for the common coil magnet.

Cu fraction in coil. Nb_3Sn strands currently used in short model R&D programs have a rather low Cu to non-Cu ratio of 0.85:1. A preliminary quench protection analysis for the above mentioned designs shows that to provide a reliable quench protection of full-scale magnets, the Cu to non-Cu ratio in the coil must be increased to 1.2:1 for the cos-theta magnet design and to 1.5:1 for the common coil design. In principle, this could be achieved either by increasing the Cu to non-Cu ratio in each individual strand or by adding pure Cu strands in the cable [6].

By using the above values for critical current margin, critical current degradation and fraction of copper in the coil, the required critical current densities of the virgin strand at 12 T and 4.2 K are shown in Table III for a nominal operation field range of 10-12 T. A reasonable target J_c(12T,4.2K) for the Nb_3Sn strand R&D should be ~3 kA/mm^2. As can be seen, at this critical current density the cos-theta design could provide a nominal operation field of 11 T, and the common coil design of 10 T with a 15% critical current margin. Some additional (~0.5-1 T) increase of the nominal operation field could be achieved if either the critical current margin or the critical current degradation were reduced.

Table III. Required critical current density in virgin strand for the Fermilab cos-theta and common coil full-scale magnet designs.

Nominal field, T	Maximum field, T	Jc(12T,4.2K), kA/mm^2	
		Cos-theta	Common coil
10	11.5	2.2	3.0
11	12.7	3.0	4.4
12	13.8	4.4	6.1

B. Effective filament diameter

The effective filament diameter and the critical current density in a strand determine the effect of coil magnetization on magnet field quality at low fields, as well as the conductor stability against flux jumps. At present, the effective filament diameter of Nb_3Sn strands with high critical current density is quite large (~100-120 microns) both for the internal tin (IT) and the modified jelly roll (MJR) processes. Magnetization measurements show that even at critical current densities as low as ~1600 A/mm^2, some magnetic instabilities can occur at low fields. Such a large effective filament diameter produces also significant coil magnetization effects, which cannot be completely compensated even with the recently proposed passive correction schemes [7-9]. However, it appears that one can reduce the effective filament diameter in Nb_3Sn strands by optimizing the strand design and/or the technological process. For strands produced using the powder in tube (PIT) technique, this value is already as low as 25-45 microns. A reduction of effective filament size for the other two techniques is also possible. Taking into account several factors, such as the target critical current density, the large dynamic field range (~15-20) required for VLHC high field magnet and the requirements for magnetic stability, the effective filament diameter in Nb3Sn strands must be reduced to 30-40 microns.

C. Cu to non-Cu

The Cu to non-Cu ratio is an important parameter for strand stabilization and, as was mentioned above, for magnet quench protection. A high Cu to non-Cu ratio is required to restrict the maximum temperature in the coil and the voltages in the magnet during quench. However, a low Cu to non-Cu ratio increases the fraction of superconductor in the coil and thus reduces the coil volume. It also improves the strand stability with respect to the thermal disturbances in the coil. An optimal Cu to non-Cu ratio depends on magnet design and parameters such as magnet bore diameter, magnet length, stored energy, inductance, etc. It should be relatively high especially in full-scale magnets. The possibility to provide magnet protection by adding pure Cu strands in the cable is under study. A parallel effort to increase the Cu to non-Cu ratio in the strand should also be undertaken.

D. Reaction cycle

The reaction cycle for Nb_3Sn strands had been optimized at relatively low temperatures (<650C) due to restrictions imposed by the conductor insulation available until recently. The resulting reaction times for IT and MJR strands were rather long, up to 600 hours. Recent results in the development of high temperature insulation materials, and Nb_3Sn heat treatment studies suggest that the reaction time can be reduced without a significant degradation of the strand performance [9]. Such a reduction in the reaction time would be very important for cost reduction, especially for the wind & react technique.

E. Conductor price

The present cost of Nb_3Sn strands exceeds the cost of NbTi strands by a factor of 5-10. Such high conductor cost increases the Nb_3Sn magnet cost by a factor of 2-3 with respect to NbTi magnets [10]. Therefore, a significant reduction of Nb_3Sn strand cost is required in order to make this technology fully attractive for the VLHC. Taking into account that the fabrication technology of Nb_3Sn strands is similar to that of NbTi strands and that it does not use any rare or expensive components, it is believed that present Nb_3Sn strand cost could be reduced by a factor of 2-3 from the present value. Obviously a sizable reduction of Nb_3Sn strand cost during large-scale production should also be expected.

IV. NB$_3$SN STRAND PROCUREMENT

The high field magnet R&D program at Fermilab was started in 1998. Its goal is the development of new cost effective designs and fabrication technologies for accelerator magnets utilizing brittle superconductors (Nb_3Sn, Nb_3Al, HTS). The plan includes fabrication and tests of short model series at a rate of 2-6 models of different designs per year. The expected need of superconducting strands to support this program is summarized in Table IV.

Table IV: Proposed Nb3Sn strand procurement plan for the Fermilab High Field Magnet R&D program.

Strand type	Strand quantity, kg				
	FY98	FY99	FY00	FY01	FY02
ITER	-	170	130	100	-
IT	20	-	31	70	120
MJR	-	-	80	70	120
PIT	-	-	40	40	40
Total:	20	170	281	280	280

V. SUMMARY

The target Nb_3Sn strand parameters for the on-going superconductor R&D efforts are summarized below:

- Strand diameter range – 0.3-1 mm
- Critical current density @12T and 4.2K – more than 3 kA/mm^2
- Effective filament size – less than 40 microns
- Cu to non-Cu ratio – up to 1.5:1
- Strand unit length – more than 1 km
- Reaction cycle – less than 200-300 h
- Conductor price – less than 200-300 $/kg

To provide the model fabrication rate of 2-6 magnets per year necessary for an efficient high field magnet R&D program, a Nb_3Sn strand procurement of 250-300 kg per year is required.

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